Dissolved Oxygen Profiles at Major Wastewater Discharges and Hydroelectric Dams on the Ohio River[1]

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ABSTRACT. Dissolved oxygen (DO) concentrations in the summer of 1987 did not change significantly along the Ohio River between Wheeling, WV and Louisville, KY. Depth variation was evident but no temperature stratification was observed. DO concentrations downstream of hydroelectric dams decreased in each case. Degassing of the water passing through the turbines may have accounted for this decrease. No correlation was found between DO concentration and volume of effluent discharged from waste water treatment plants (WWTP). Elevated DO concentrations existed at and below WWTPs, indicative of the general effectiveness of WWTP reaeration on DO concentrations at the point of discharge and approximately one mi down river. WWTPs in the highly urbanized Cincinnati area yielded results similar to the WWTPs as a whole, but a slight sag was evident at the Dry Creek WWTP. A hypothetical grab-sample taken at 1.5 m depth at mid-channel was compared to the mean obtained from a nine-sample-profile. The variation was not significant, indicating that grab-sampling would be equivalent to more detailed and expensive profile sampling under similar flow conditions in the river.

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INTRODUCTION

The Ohio River is a complex, dynamic system affected by many varied conditions which may influence the dissolved oxygen (DO) levels. Carbonaceous biochemical oxygen demand (CBOD), nitrogenous biochemical oxygen demand (NBOD), photosynthesis, algae, travel and mixing times of pollutants, and diel effects are several of the possible major factors governing the DO concentration in the river. The classical model of DO concentration in a river is the DO sag curve (Hammer and MacKichan 1981). In this model, DO levels decrease at and downstream from any effluent input that has an oxygen demand. Further downstream, when oxygen demand has been satisfied, DO levels return to a natural state. However, this model may be altered for many different conditions as influenced by the above. For instance, the effluent from a discharge may travel many mi before mixing sufficiently with river water to produce a sag, while algae may consume nutrient rich effluent and produce higher levels of oxygen in the water. The analytical imprecision of instruments, DO variation across a stream, and loading rates must also be taken into account in establishing a DO data base for a given stream.

The focus of this study is to use measured DO concentrations as a practical parameter important to aquatic, aerobic species. Of specific interest are the effects of major wastewater treatment plant effluents as defined by the Ohio River Valley Water Sanitation Commission (ORSANCO) ($>38 \times 10^3$ m^3/day (10 mgd)) and hydroelectric dams.

MATERIALS AND METHODS

This study investigated the effect of hydroelectric dams and major wastewater treatment plant effluents on DO levels in the Ohio River between Pittsburgh, PA and Louisville, KY, from 22 July to 1 August 1987, on the research vessel "Boatload of Knowledge" (Mitsch et al. 1989). Three hydroelectric dams are in operation on this reach of the river (Fig. 1). They are located at Racine (River Mile [RM] 237.5), Greenup (RM 341), and Markland (RM 531.5). Major wastewater discharges (Fig. 1) occur at Wheeling, WV (57×10^3 m^3/day), Huntington, WV (64×10^3 m^3/day), and four discharges in the greater Cincinnati area: Little Miami, OH (140×10^3 m^3/day), Mill Creek, OH (450×10^3 m^3/day), Dry Creek, KY (110×10^3 m^3/day), and Muddy Creek, OH (57×10^3 m^3/day).

Sampling of DO was performed at the middle of the channel and approximately one-third of the distance from each bank, and readings were taken at three depths: 0.3, 1.5, and 4.6 m (Fig. 2). These cross-sectional readings were then combined to find a mean DO concentration at each site. DO concentrations were measured above and below hydroelectric dams/locks and approximately one mi above, at, and one mi below the wastewater discharge points (Fig. 2).

The procedure for sampling DO was followed as outlined in the U.S. Geological Survey's National Water Quality Assessment Program (White 1987). Field sheets from the above program were used as the guideline for data collection. Measurements were taken with a YSI portable DO meter which provided water temperature as well as DO readings. The precision of this instrument was ± 0.5 mg/L for DO. The instrument was calibrated on a daily basis prior to sampling. Specific conductivity of the water, weather conditions (air temperature, barometric pressure, visibility, precipitation), water conditions (color, turbidity), and surrounding land use were noted. DO saturation percentages were also calculated.

Although sampling was carried out at the nine sites over a time frame of 11 days, the study should be considered as a synoptic procedure because of the river's low velocity when compared to the short travel time (11 days) it took the boat to cover the approximately 700 km. An attempt was made to sample each site at approximately the same time of day in order to avoid aberrations in measurements resulting from diel changes. However, this was not possible in all cases since the schedule upon which the journey relied was restricted. Sampling was performed at Wheeling and Huntington in the early to mid-morning hr under clear skies. Originally, it was intended to sample at a constant depth of one m. Experimental readings below Wheeling showed that there was no temperature stratification but significant DO change with depth. With this discovery, the procedure was altered to sample at the depths of 0.3, 1.5, and 4.6 m.

The Racine Dam was sampled in the mid-morning under clear skies and the Greenup Dam was sampled in the early afternoon under partly cloudy skies. In the late afternoon of 30 July, as the boat approached Cincinnati, measurements were taken above the Little Miami River. On the afternoon of 31 July, measurements were taken at Mill Creek, Dry Creek, and Muddy Creek in succession under threatening skies which eventually yielded a light drizzle, suspending sampling before Muddy Creek was complete. On the afternoon of 1 August, the boat passed through Markland Dam under overcast skies to complete sampling.

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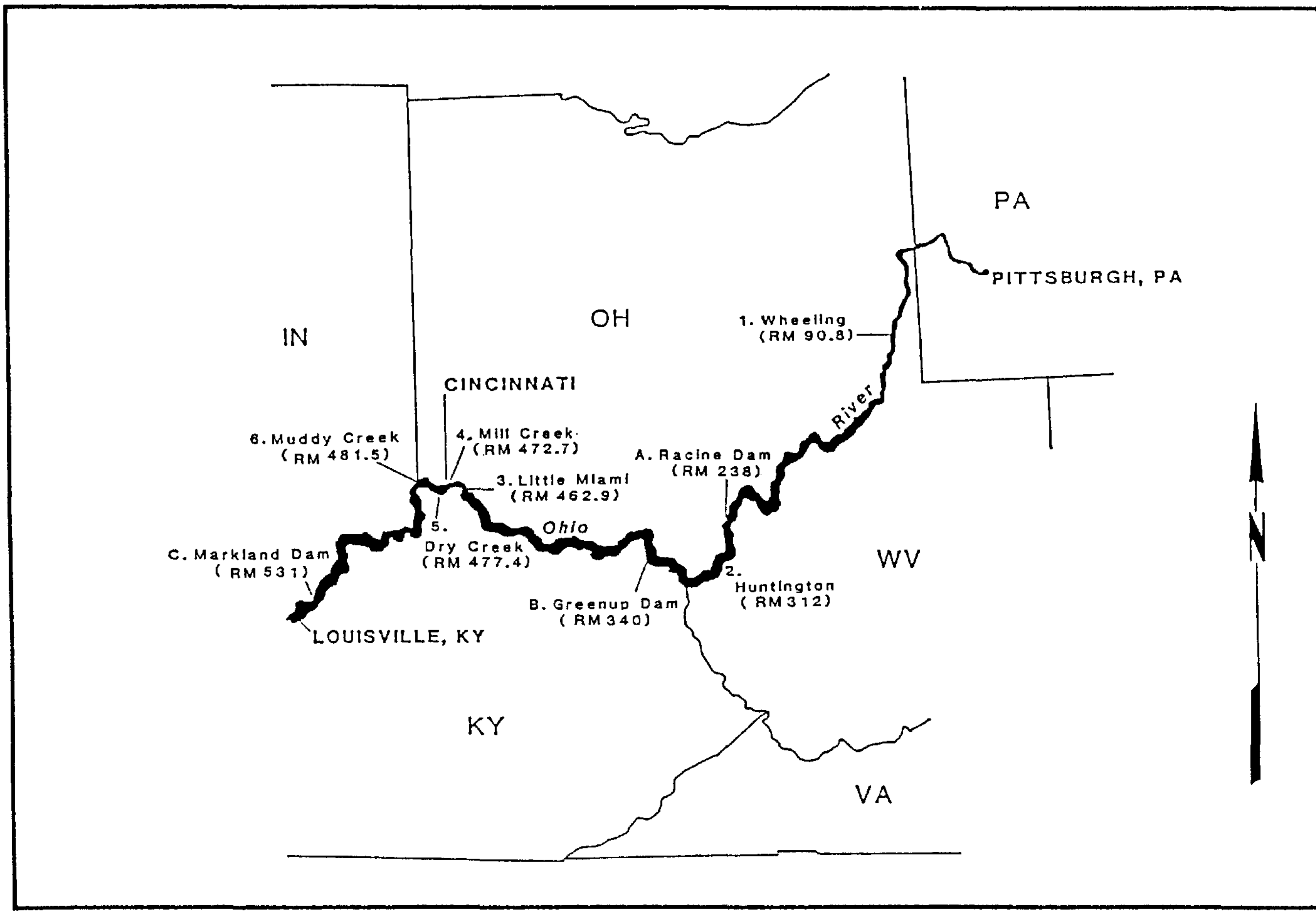

FIGURE 1. Ohio River map showing dissolved oxygen sampling locations at wastewater discharges (numbers) and hydroelectric dams (letters).

The collected data were analyzed using SAS (1982) statistical software on the IBM 3090 at the University of Kentucky Computing Center. The General Linear Models (GLM) procedure was chosen, given the unbalanced nature of the data set. The variables analyzed consisted of the following:

1. SITES: Racine Dam
   Huntington WWTP
   Greenup Dam
   Little Miami WWTP
   Mill Creek WWTP
   Dry Creek WWTP
   Muddy Creek WWTP
   Markland Dam
2. LOCATIONS: Above, At, and Below WWTPs
   Above and Below hydroelectric dams
3. DEPTHS: 0.3, 1.5, and 4.6 m at mid-channel, north bank, and south bank

Combinations of these variables yielded a total of 159 DO observations.

Tukey's standardized range test was used to determine the existence of separate populations within the variables Sites and Depths. This test was chosen from the other GLM tests for its conservative nature. That is, Tukey's test is unlikely to find means different unless they are significantly different (Stephen Lowry pers. commun.).

RESULTS AND DISCUSSION

General Observations

Two types of sampling sites, hydroelectric power dams (Table 1) and wastewater treatment plants (WWTP) (Table 2) were targeted. It was anticipated that effluent from WWTPs would depress DO concentration, whereas the hydroelectric power dams would be points of reaeration along the river.

There was no pronounced decrease in DO concentration from the upper reaches of the Ohio River near Wheeling, WV (RM 91) to Markland Dam (RM 531) (Fig. 2). Although certain sites (Huntington, Greenup Dam, Little Miami, Dry Creek, and Markland Dam) had depressed DO concentrations, there were also high DO concentrations interspersed downstream, most notably at the Mill Creek and Muddy Creek sampling points.

Four distinct groups were identified which had no relation as far as site type or site ranking downstream are concerned (Table 3). The absence of site relationships suggests that other factors play a part in controlling DO concentrations. These factors may include photosynthesis, surrounding land use, and river traffic.

The means of DO at the three depths are all significantly different (Table 4). The presence of higher mean DO concentrations toward the water surface suggests that near-surface phenomena, such as photosynthesis, and surface disturbances, such as river traffic or wind, may play major roles in DO concentrations. Temperature effects are discounted because, at a given location, no temperature stratification was observed down to a depth of 4.6 m. The results of Tukey's test indicate that DO concentration was not necessarily site-specific but was definitely depth-dependent (Tables 3 and 4).

Hydroelectric Power Plants

All dams surveyed (Figs. 1 and 3, see Racine, Greenup, and Markland) showed lower mean DO concentration

TABLE 1

Dissolved oxygen concentrations (mg/L) above and below hydroelectric power dams on the Ohio River, July 22-August 1.

Site location	Sample depth (m)	South bank	Mid-channel	North bank	Mean DO (mg/L)
Racine Dam	RM 237.5				
Above	0.3	9.60	9.80	9.80	
	1.5	9.80	9.60	9.60	
	4.6	9.10	8.95	9.20	9.49
Below	0.3	8.90	9.10	9.30	
	1.5	9.00	9.30	9.30	
	4.6	9.20	9.20	8.80	9.12
Greenup Dam	RM 341				
Above	0.3	6.80	7.45	7.50	
	1.5	6.75	6.90	6.95	
	4.6	6.10	6.30	6.65	6.82
Below	0.3	6.60	6.60	6.70	
	1.5	6.70	6.65	6.60	
	4.6	6.80	6.50	6.25	6.60
Markland Dam	RM 531.5				
Above	0.3	7.45	7.40	7.20	
	1.5	5.80	6.10	6.50	
	4.6	4.80	4.75	4.80	6.09
Below	0.3	5.70	5.55	5.80	
	1.5	5.40	5.50	5.75	
	4.6	4.50	4.40	5.90	5.39

TABLE 3

Tukey's studentized range test for the variable dissolved oxygen at all sites.[a]

Grouping[b]	Mean mg/L	Site	Site rank downstream	Site type
A	9.31	Racine	1	Dam
B	8.33	Mill Creek	5	WWTP
B	7.67	Muddy Creek	7	WWTP
C	6.71	Greenup	3	Dam
C D	6.43	Dry Creek	6	WWTP
C D	6.07	Huntington	2	WWTP
C D	5.96	Little Miami	4	WWTP
D	5.74	Markland	8	Dam

Standard Error = 0.06279

[a]Test of Ho: Means are not significantly different; selected and calculated parameters: alpha = 0.05; mean squared error = 0.626832; df = 120; critical value of studentized range = 4.36; harmonic mean of cell sizes = 17.56.

[b]Means with the same letter are not significantly different.

TABLE 4

Tukey's studentized range test for the variable dissolved oxygen at depth for all sites.[a]

Grouping[b]	Mean (mg/L)	Depth (m)
A	7.84	0.3
B	7.28	1.5
C	6.06	4.6

Standard Error = 0.06279

[a]Test of Ho: Means are not significantly different; selected and calculated parameters: alpha = 0.05; df = 12; critical value of studentized range = 3.36.

[b]Means with the same letter are not significantly different.

TABLE 5

Tukey's studentized range test for the variable dissolved oxygen at locations for dams.[a]

Grouping[b]	Mean (mg/L)	Site	Location
A	9.49	Racine	Above
B	9.12	Racine	Below
C	6.82	Greenup	Above
C	6.60	Greenup	Below
D	6.08	Markland	Above
E	5.39	Markland	Below

[a]Test of Ho: Means are not significantly different; selected and calculated parameters: alpha = 0.05; df = 12; critical value of studentized range = 3.08.

[b]Means with the same letter are not significantly different.

TABLE 6

Tukey's studentized range test for the variable dissolved oxygen at depths for dams.[a]

Grouping[b]	Mean (mg/L)	Depth (m)	Site
A	9.43	1.5	Racine
A	9.41	0.3	Racine
B	9.07	4.6	Racine
C	6.94	0.3	Greenup
C	6.76	1.5	Greenup
D	6.43	4.6	Greenup
E	6.52	0.3	Markland
F	5.84	1.5	Markland
G	4.85	4.6	Markland

[a]Test of Ho: Means are not significantly different; selected and calculated parameters: alpha = 0.05; df = 12; critical value of studentized range = 3.77.

[b]Means with the same letter are not significantly different.

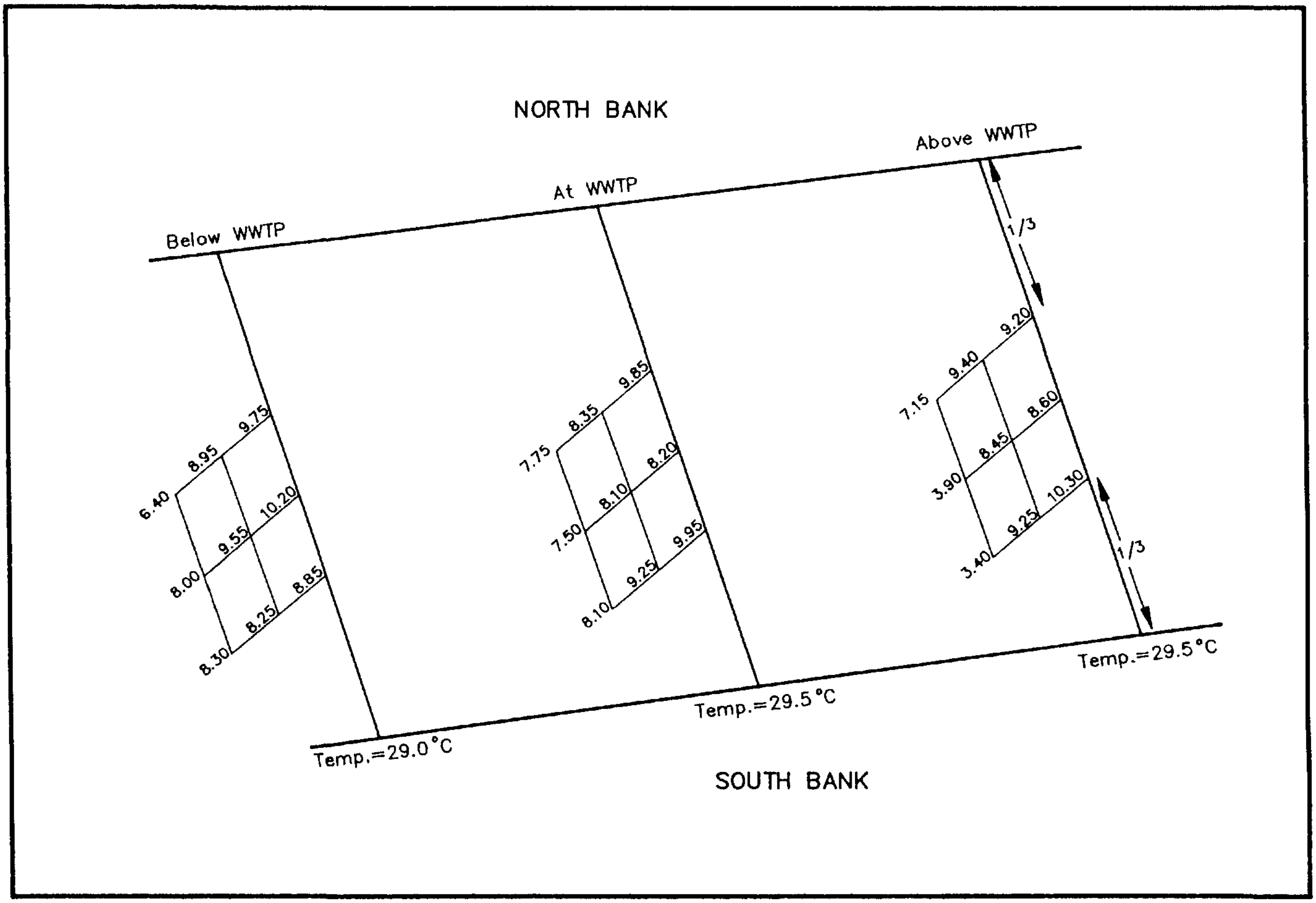

FIGURE 2. Example of cross-section sampling results for dissolved oxygen concentrations in the Ohio River in the vicinity of Mill Creek wastewater treatment plant, afternoon of 31 July 1987 (RM 472-474).

below the dam than above the dam (Table 1). The initial assumption was that hydroelectric power generation might in some way serve to aerate the water. On the basis of the measurements obtained, this was not the case. Hydroelectric turbines are below the surface of the water and, therefore, would not necessarily introduce oxygen into the system. Degassing of the water as it passes through the turbines may account for the lower DO concentration downstream of each of the three dams (David Kao pers. commun.). In addition, potential reaeration by water flowing over the dam was at a minimum because of the low flow conditions during the sampling period.

Tukey's standardized range test was utilized to evaluate the variable location at each site (Table 5). At Racine and Markland Dams, there is a significant difference in the DO concentrations above and below the dams. The difference, however, at the Greenup Dam is not significant.

The three depth measurements at Markland Dam (Table 6) produced three separate populations, whereas the measurements from Racine and Greenup Dams grouped the 0.3 m and 1.5 m concentrations into a population separate from the 4.6 m measurements. From data collected during this study, it is not clear why these differences in DO concentrations exist.

Wastewater Treatment Plants

All Huntington area sampling points (Fig. 3; RM 311, 312, and 313) had low DO concentrations when compared to most other sample sites. This is an unexpected result because the Huntington wastewater treatment plant has a moderate discharge (64×10^3 m^3/day) and is located a significant distance downstream (350 km) from the previous major wastewater discharge at Wheeling.

The Little Miami treatment plant did not yield a full suite of data. No outfall could be located, and conditions prevented readings being taken at or below the Little Miami River.

Data collected along the entire river indicate that there was no direct correlation between the volume of effluent discharge and DO concentrations measured in the vicinity of the WWTP outfalls. For example, Mill Creek wastewater treatment plant had the largest volume of effluent discharge (450×10^3 m^3/day) but one of the highest observed DO concentrations (Fig. 3). On the other hand, Dry Creek had an effluent discharge of approximately 110×10^3 m^3/day, but the DO concentrations were depressed at this point. Possible causes of variations include algal activity, effluent travel time and mixing, diel variations, CBOD, and NBOD (Bob Davidson pers. commun.). All of these variables could independently or collectively produce the measured results.

In general, the data do not indicate the existence of a classical DO sag curve in the vicinity of each effluent discharge site except for Dry Creek, where a slight drop in DO concentration exists at the outfall (Fig. 3). By inspection, the water quality appeared to improve in a one mi

TABLE 2

Dissolved oxygen concentrations (mg/L) above, at, and below wastewater treatment plant discharges on Ohio River, July 22-August 1.

Site location	Sample depth (m)	South bank	Mid-channel	North bank	Mean DO (mg/L)
Wheeling, WV	RM 90.8	Discharge = 64.0 × 10^3 m^3/d			
Above	1.0	8.10	8.00	8.15	8.08
At	1.0	7.95	8.10	8.80	8.28
Below	1.0	8.60	9.10	10.00	9.23
Huntington, WV	RM 312	Discharge = 64.0 × 10^3 m^3/d			
Above	0.3	6.05	6.40	6.40	
	1.5	6.10	6.45	6.80	
	4.6	5.00	5.00	1.70	5.54
At	0.3	6.40	6.30	6.25	
	1.5	6.30	6.40	6.30	
	4.6	6.65	6.15	6.20	6.33
Below	0.3	6.40	6.40	6.35	
	1.5	6.35	6.30	6.25	
	4.6	6.10	6.35	6.50	6.33
Little Miami, OH	RM 462.9	Discharge = 140.0 × 10^3 m^3/d			
Above	0.3	7.80	8.90	11.20	
	1.5	3.10	3.90	9.30	
	4.6	1.80	3.80	3.80	5.96
Mill Creek, OH	RM 472.7	Discharge = 450.0 × 10^3 m^3/d			
Above	0.3	10.30	8.60	9.20	
	1.5	9.25	8.45	9.40	
	4.6	3.40	3.90	7.15	7.74
At	0.3	9.95	8.20	9.85	
	1.5	9.25	8.10	8.35	
	4.6	8.10	7.50	7.75	8.56
Below	0.3	8.85	10.20	9.75	
	1.5	8.25	9.55	8.95	
	4.6	8.30	8.00	6.40	8.69
Dry Creek, KY	RM 477.4	Discharge = 110.0 × 10^3 m^3/d			
Above	0.3	7.50	7.30	7.20	
	1.5	7.10	6.80	6.80	
	4.6	5.30	5.15	5.15	6.48
At	0.3	7.00	6.40	7.15	
	1.5	6.75	7.00	6.40	
	4.6	5.20	5.20	5.10	6.24
Below	0.3	7.95	7.20	8.10	
	1.5	7.25	6.65	6.30	
	4.6	4.95	5.20	5.40	6.56
Muddy Creek, OH	RM 481.5	Discharge = 57.0 × 10^3 m^3/d			
Above	0.3	8.30	7.70	8.70	
	1.5	7.70	7.50	8.50	
	4.6	6.30	6.20	7.20	7.57
At	0.3	*	*	8.40	
	1.5	*	*	8.00	
	4.6	*	*	6.20	7.53
Below	0.3	*	*	9.40	
	1.5	*	*	7.95	
	4.6	*	*	6.95	8.10

*Data not collected.

reach below the effluent discharges except at Huntington, where it remained the same. This observation, that water quality improved below effluent discharges, was statistically tested using Tukey's test (Tables 7 and 8). The mean DO concentrations at the Mill Creek and Muddy Creek sites are not significantly different, and the means of the Dry Creek and Huntington sites are also not significantly different. The difference between these two groups does not correlate to downstream rank or effluent discharge rate (Table 7), so this difference must be caused by one or more of the factors previously mentioned but not measured in this study.

Statistical analysis indicates that the DO concentrations above WWTPs were lower and can be grouped with those concentrations at WWTPs (Table 8). Also, DO concentrations below WWTPs were the highest and are not significantly different from the DO means at WWTPs (Table 8). This analysis further indicates that WWTPs actually enhanced water quality with respect to DO concentrations at and at least one mi below the outfall. Increased DO probably results from reaeration of the treated effluent before discharge to the river.

Tukey's Studentized range test was also applied to the variable depth for the WWTP sites (Table 9). The re-

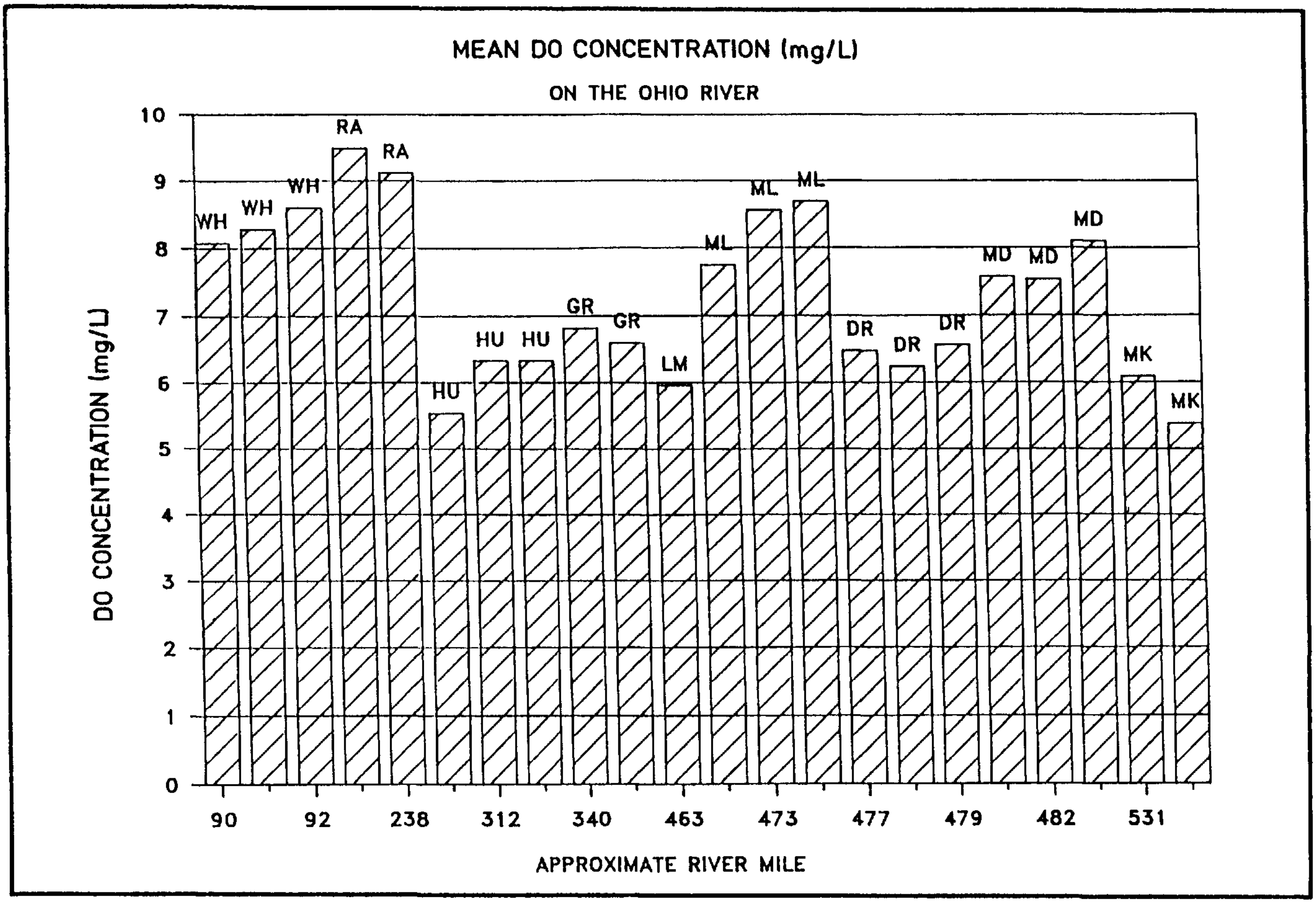

FIGURE 3. Mean dissolved oxygen concentrations on the Ohio River by river mile.

TABLE 7

Tukey's studentized range test for the variable dissolved oxygen at wastewater treatment plant sites.[a]

Grouping[b]	Mean (mg/L)	Site	Downstream rank	Effluent discharge (m^3/day)
A	8.33	Mill Creek	2	45×10^3
A	7.67	Muddy Creek	4	57×10^3
B	6.42	Dry Creek	3	10×10^3
B	6.07	Huntington	1	64×10^3

Standard Error = 0.07470

[a]Test of Ho: Means are not significantly different; selected and calculated parameters: alpha = 0.05; df = 72; critical value of studentized range = 3.72; harmonic mean of cell sizes = 22.50.

[b]Means with the same letter are not significantly different.

TABLE 8

Tukey's studentized range test for the variable dissolved oxygen at wastewater treatment plant locations.[a]

Grouping[b]	Mean (mg/L)	Location
A	6.83	Above
B A	7.09	At
B	7.28	Below

Standard Error = 0.07470

[a]Test of Ho: Means are not significantly different; selected and calculated parameters: alpha = 0.05; df = 72; critical value of studentized range = 3.38; harmonic mean of cell sizes = 31.76.

[b]Means with the same letter are not significantly different.

sults indicate that DO concentrations at the three depths are significantly different, as was found to be the case using all the data (WWTP and dam sites).

Cincinnati Area

The presence of four major wastewater discharges in a 30-km reach of the Ohio River in the highly urbanized Cincinnati metropolitan area presented an opportunity to evaluate anthropogenic effects upon Ohio River water quality. It was anticipated that an area such as this might produce a very noticeable sag in the DO concentrations. This assumption was investigated by inspection and statistical analysis. DO measured at Muddy Creek (RM 481.5) was expected to be the lowest because this site is in proximity and downstream from the effluent discharges of Mill Creek (450×10^3 m^3/day) and Dry Creek (110×10^3 m^3/day). However, the DO concentration at Muddy Creek was elevated when compared with Little Miami (RM 463) and Dry Creek (RM 477-479).

Tukey's test was employed to determine whether there was a statistically significant difference in the means of the sites (Table 10). Results indicated that the three sites

TABLE 9

Tukey's studentized range test for the variable dissolved oxygen at wastewater treatment plants by depths.[a]

Grouping[b]	Mean (mg/L)	Depth (m)
A	7.82	0.3
B	7.42	1.5
C	5.93	4.6

Standard Error = 0.07470

[a]Test of Ho: Means are not significantly different; selected and calculated parameters: alpha = 0.05; df = 72; critical value of studentized range = 3.38.

[b]Means with the same letter are not significantly different.

TABLE 10

Tukey's studentized range test for the variable dissolved oxygen at sites in the Cincinnati area.[a]

Grouping[b]	Mean (mg/L)	Site	Downstream ranking
A	8.33	Mill Creek	1
B	7.67	Muddy Creek	3
C	6.42	Dry Creek	2

Standard Error = 0.09124

[a]Test of Ho: Means are not significantly different; selected and calculated parameters: alpha = 0.05; df = 50; critical value of studentized range = 3.42; harmonic mean of cell size = 21.32.

[b]Means with the same letter are not significantly different.

in the Cincinnati area had mean DO values which are significantly different. In addition, comparison of the calculated means indicated that a DO sag was present at

TABLE 11

Tukey's studentized range test for the variable dissolved oxygen at sites in the Cincinnati area.[a]

Grouping[b]	Mean (mg/L)	Depth (m)
A	8.33	0.3
B	7.67	1.5
C	6.42	4.6

Standard Error = 0.09124

[a]Test of Ho: Means are not significantly different; selected and calculated parameters: alpha = 0.05; df = 50; critical value of studentized range = 3.42.

[b]Means with the same letter are not significantly different.

Dry Creek, the middle sampling point in the Cincinnati area. Although a sag existed, DO concentration was above the minimum acceptable level of 5 mg/L established by the U.S. EPA.

Concerning variable depth, DO means are significantly different among the three depths, 0.3, 1.5, and 4.6 m (Table 11). This result is consistent with each type of sampling site throughout the survey.

Grab Samples vs. Cross-Sectional Sampling

ORSANCO routinely takes grab samples from mid-channel at a constant depth to monitor the quality of the Ohio River in addition to their electronic monitors (Peter Tennant pers. commun.). One interesting aspect of the present study was the opportunity to test the variation between DO concentration, as measured by a grab sample, to the mean DO concentration calculated from

TABLE 12

Student's t-test of grab samples vs. cross-sectional sampling.

Site	Location	DO Conc. at mid-channel 1.5m (mg/L)	Mean DO location (mg/L)	t-calc	delta Mean-1.5m
Racine	Above	9.60	9.49	1.03	−0.11
Racine	Below	9.30	9.12	0.01	−0.18
Huntington	Above	6.45	5.54	0.44	−0.91
Huntington	At	6.40	6.33	0.09	−0.07
Huntington	Below	6.30	6.33	0.04	+0.03
Greenup	Above	6.90	6.08	1.14	−0.82
Greenup	Below	6.65	6.60	1.00	−0.05
L. Miami	Above	3.90	5.96	2.47*	+2.06
Mill Creek	Above	8.45	7.74	1.37	−0.71
Mill Creek	At	8.10	8.56	0.40	+0.46
Mill Creek	Below	9.55	8.69	0.85	−0.86
Dry Creek	Above	6.80	6.48	0.98	−0.32
Dry Creek	At	7.00	6.24	2.69*	−0.76
Dry Creek	Below	6.65	6.56	0.15	−0.09
Muddy Creek	Above	7.50	7.57	0.23	+0.07
Markland	Above	6.10	6.09	0.02	−0.01
Markland	Below	5.50	5.39	0.59	−0.11

*: Ho is rejected.

Ho: Means are not significantly different; selected and calculated parameters: alpha = 0.05; df = 8; t-table = 1.86.

a cross-sectional sample consisting of nine measurements. For this experiment, the mid-channel 1.5 m depth DO concentration was selected as the "grab sample" for each cross-section. The significance of the difference between this value and the mean DO value for the cross-section, as computed using the nine DO values available at the location, was analyzed using the Student's t-test (Snedecor and Cochran 1963).

With the exception of two locations of the seventeen tested, the t-test indicates that there is no significant statistical difference between a single grab sample and a cross-sectional mean calculated from nine measurements (Table 12). Therefore, it can be suggested with confidence that a single grab sample taken from a depth of 1.5 m is as representative of DO concentration as a mean calculated from the nine-point sample profile used in this study. From an economic standpoint, grab sampling reduces the cost of determining DO concentrations. However, profiling may be necessary to confirm grab samples and to address special problems concerning DO concentration, such as those indicated by the data collected at Little Miami and Dry Creek WWTPs, or for lower flow conditions when mixing may not be as effective in the river regime.

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